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SEISMIC EVALUATION AND DESIGN OF JACK ARCH SLABS

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SUMMARY

The masonry jack arch slabs are used extensively in some parts of the world to floor residential and industrial buildings. The popularity of this flooring system stems from its relatively low cost and easy construction. This old system of flooring has shown robustness and resilience under normal gravity loading but lacks the criteria for an earthquake resistant slab. In this paper, the weaknesses inherent in the traditional jack arch slab are first explored. An engineered, earthquake resistant version of the slab is then presented and the parameters affecting design of the slab are discussed. It is concluded that the engineered jack arch slabs discussed in this paper can be suitable alternatives to other forms of flooring in earthquake prone areas.

INTRODUCTION

The steel I-beam, jack-arch flooring system was developed in early Victorian Britain and was used to cover large floor areas at warehouses, factories and other industrial buildings. The new flooring technique was later adopted in North America, East Europe and the Indian subcontinent. By the middle of the twentieth century it became a popular flooring system in many Middle Eastern countries. Because of a number of inherent advantages, the traditional jack-arch slabs are still very popular in the Middle East, particularly in Iran where, not only industrial buildings and ordinary dwellings but also many medium to high rise steel and concrete framed buildings are also floored by this method. Some of these advantages include; simple construction technique, speed in construction, low cost of construction and the ability to alter the slab after construction.

The floor slabs constructed using the steel I-beam, jack arch system are stable under normal static conditions as the brick arches transfer the gravity loads mainly in compression along the arch to the supporting beams. The load is then transferred along the individual, unconnected parallel steel beams to the supporting walls or beams. The geometric form of the steel I-beam jack-arch system and the load path through the steel beams make the slab act as a one-way system.

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Despite the wide spread use of the jack-arch slabs and their advantages, there are no particular procedures for their engineered design and there is no mention of the system in codes of practice. Design engineers using the jack-arch slab in framed buildings, consider the brick arches as merely dead loads carried by the steel beams and suffice with designing the steel beams. By this assumption they ignore the large stresses developed in brick arches due to gravity and out of plane dynamic loads. Despite the lack of a proper design basis and the poor performance of the traditional jack-arch system under earthquake loading, this type of flooring is still used extensively in many countries.

SEISMIC PERFORMANCE OF TRADITIONAL JACK-ARCH SLABS

The performance of the traditional one-way jack-arch slabs in a number of recent earthquakes in Eastern Europe and the Middle East has been generally poor. Collapse of a large number of jack-arch slabs and damage to many more was reported from the Romanian earthquake of 1990, the Manjil, Iran earthquake of 1990 [1,2] and the recent Bam, Iran earthquake of December 2003 [3]. These earthquakes provided real testing grounds for different forms of the one-way jack-arch system. Typical weaknesses and modes of failure of the traditional one-way slabs can be categorised as follows:

i) Movement of simply supported steel beams from their position under earthquake shaking, causing the collapse of brick arches. This is the most common mode of failure in the slabs resting on load-bearing masonry walls (Figure 1). Restraining the ends of the I-beams with transverse steel beams, or fixing the ends of the beams to the concrete ring beam and using transverse or diagonal steel tie bars over the span are two earlier recommendations for keeping the beams in place [4]. These recommendations are adopted in many buildings in Iran with beneficial results.

Fig. 1 Damage to the traditional jack arch slab during Bam earthquake of 2003

ii) Inability of the brick arches to transfer in-plane loads in the direction perpendicular to the steel beams.
iii) Concentration of stresses in the stiff brick arches due to out-of-plane vibration of the slab. Under the vertical component of ground motion, slabs undergo large out-of-plane (bending) vibration. The geometry of the brick arches makes them far stiffer than the steel beams in vertical vibration. Therefore, the stresses tend to concentrate in the stiff brick arches rather than the more flexible steel-beams.
iv) The weakness of slab system in transferring in-plane shear. Earthquake-induced torsion in asymmetric buildings results in application of large in-plane shear forces to the slab. The unconnected steel beams provide little resistance in this regard. A large portion of this load is, therefore, received by brick arches, which, for the reason mentioned in (ii), are unable to transfer the load.
v) The difference in dynamic properties of stiff brick arches and the more flexible steel beams is apparent. Under the vertical vibration of the slab, a dynamic interaction may occur between the two elements, resulting in the failure of the stiffer and in this case weaker system, i.e. the brick arches.
vi) The ill-connected composite form of the one-way slab does not allow for a diaphragm action of the slab as is required for good seismic performance. If a part of the load-bearing wall or supporting beam fails, the unsupported section of the slab also fails. The local failure can not be supported by other parts of the slab.
vii) The type of brick and mortar used for construction of arches is also of prime importance. The strength of the arch is governed by its weakest element i.e. mortar or more often the connection between mortar and bricks. Using heavy solid bricks, as is the normal practice, not only does not increase the strength of the arch but results in a heavy slab, increasing the gravity and seismic loads. The use of lightweight perforated bricks greatly enhances the strength and performance of the arches.
viii) Poor workmanship is another shortcoming of the one-way jack-arch slab. The ability of the brick-arch to transfer the load in compression depends on the rise of the arch. Some masons tend to reduce the rise of each as much as possible so that the amount of plaster required making a flat surface, is reduced.

The above factors make the unanchored traditional jack-arch system unsuitable for earthquake prone areas. Considering the apparent popularity of the jack arch system, Iranian seismic code proposes to join the parallel beams together at their end using transverse beams and/ or using tie bars to join these beams together. The Manjil earthquake of 1990 and particularly the Bam earthquake of 2003 showed a better seismic performance for the code-recommended anchored slabs. Some anchored slabs however showed signs of failure due to the dynamic interaction between the steel beams and masonry jack arches.

Considering that the Iranian seismic code only addresses some of the weaknesses of the traditional slab and the slab is still considered as a non-engineered slab without guidelines for its engineering design and construction, it is useful to address the weaknesses of the system and introduce methods to overcome such weaknesses and provide procedures for calculation of loading, analysis and design with a view of providing a suitable engineered slab.

THE ENGINEERED, JACK-ARCH SYSTEM

To overcome the shortcomings of the one-way jack-arch slab, the author has recently proposed to use a steel grid by including a number of transverse steel beams spanned between the main I-beams, joining these beams together at certain locations along their span [2]. In this way the unconnected parallel steel beams will become part of an inter-connected steel grid, allowing the vertical loads to be transferred in two directions and enabling the transfer of the in-plane forces with little help from the brick arches. In fact, by using a steel grid, the grid will act as the main load carrying element in the slab while the brick arches act mainly as in-fill panels, required to carry their own loads alone. The proposed two-way, steel grid, jack-arch system therefore addresses all the weaknesses of the traditional one-way slab as discussed below:

i) The steel grid will confine the brick arches in small (steel framed) panels where no differential movements of supporting steel occur during an earthquake and the arches therefore remain in place.

ii) The weakness of the one-way slab in transferring the transverse in-plane loads through the brick arches is overcome by inclusion of transverse steel beams.

iii) By creating a stiff steel grid, the in-plane shear forces will be directed towards the steel grids and away from the brick arches, hence the build up of stresses in brick arches is avoided.

iv) The long continuous brick arches of the one-way system undergo large out-of-plane displacements and considering their high stiffness in this direction, large bending stresses develop in them. In a two-way grid system, the brick arches will be made discontinuous at the location of transverse beams and become divided into a number of smaller panels with much smaller out-of-plane bending stresses.

v) Discontinuity of brick arches at the location of transverse beams also act as plastic hinges which in turn reduces the overall stiffness of brick arches. On the other hand, a steel grid will be stiffer than individual I-beams. Therefore, the two systems will be dynamically more compatible and the effects of dynamic interaction will be reduced.

vi) The steel grid creates a homogeneous diaphragm action for the slab in such a way that if some local failure in supporting walls or girder beams occurs the load from the unsupported part of the slab will be carried by the continuous grid. This will stop the partial collapse of the slab.

vii) As mentioned earlier, the problem of heavy solid bricks can be overcome by using lightweight perforated bricks. Perforations in bricks help to increase the bond between mortar and brick units. The mortar used for construction of brick arches is usually a mixture of gypsum or lime and high clay content, fine soil. This mortar is very suitable for the task, because for the mason to lay the bricks in a shallow arch a fast setting mortar will be required. Apart from the practical reasons, the gypsum-clay mortar is more flexible and ductile than cement mortar. The combination of perforated lightweight bricks and gypsum-clay mortar provides strong, yet more flexible, ductile and lightweight arch panels with better seismic performance.

viii) Finally, the use of a steel grid as opposed to individual parallel steel beams does not necessarily increase the amount of steel required for the slab. In many instances, it may in fact reduce the amount of necessary steel and therefore reduce the cost of the slab. The reason for this being that the steel grid creates a two-way action for the slab and as some of the load is transferred to the supports by the transverse beams, the load on the main longitudinal beams is reduced and smaller sections will therefore be required. This point will be discussed further in due course.

DESIGN METHOD

The jack arch slab is primarily a masonry construction. In the one-way system, brick arches undergo large stresses as they transfer the static and seismic loads to the steel beams. In the two-way system, although the role of brick arches in the transfer of loads is reduced, they are still required to transfer their own loads. The masonry buildings and steel buildings may be designed using the Allowable (Working) Stress Design method (ASD). It is, therefore, plausible to base the design of steel-beam jack arch slabs on the same method.

The design procedure is based on designing the steel grid, as the main load-bearing element, and controlling the brick arches for allowable stresses. The failure criterion for the slab is assumed to be bending failure of the steel beams or compressive failure of the brick arches. In steel beams, shear failure is unlikely to occur prior to bending failure. The tensile failure in brick arches is governed by the bond tensile strength. The bond tensile strength in masonry construction is low. Tensile bond failure between brick units and mortar will be allowed under high frequency cyclic loads since this failure does not affect the load-carrying capability of brick arches in compression.

LOADING

Loading to be considered in the design of jack arch slabs, are gravity and earthquake loads. The gravity, service dead and live loads may be determined using appropriate codes of practice. The earthquake loads, however, warrant further discussion. The earthquake loads, acting on a jack arch slab are; in-plane horizontal loads and out-of-plane vertical loads.

Horizontal earthquake loads

The earthquake-induced horizontal forces acting on the slab may be either in-plane axial or in-plane shear forces. The in-plane axial forces are caused by the inertia of the slab alone. These forces are generally small and the resulting stresses are minimal. The in-plane axial forces, therefore, are neglected for design purposes. The in-plane shear forces, however, may be large and should be considered in design. These forces are the result of differential movements of the parallel slab supports caused by the torsion in the building. The horizontal shear force acting on the slab may be determined by analyzing the building for earthquake loads, using an equivalent-static, a pseudo-dynamic or a dynamic method.

In a two-way jack arch system, in-plane shear force is carried mainly by the frame action of the steel grid, whereas, in a one-way system, the brick arches are the main load-carrying elements. The brick arches are weak in transferring in-plane stresses, therefore, the steel grid should carry the majority of the load. In other words, a one-way system will not be suitable when large in-plane shears are present. For the two-way system, the shear-induced stresses in both the steel grid and the brick arches should be checked against the allowable stresses.

Vertical earthquake loads

Considering that the majority of stresses developed in the slab are due to the combined effects of gravity and vertical earthquake loads design of the slab will be governed by the out-of-plane bending of the steel beams. Out-of-plane shear stresses in both the steel beams and the brick arches should also be checked against the allowable stresses.

To determine the vertical earthquake loads, the simple, equivalent-static, method is used. In this method, the earthquake load, E, is related to the weight of the system, W_e, in the following form:

$$E = CW_e \qquad (1)$$

W_e, is usually considered as the total dead load plus a percentage of the live load, the recommendation for which differs in seismic codes for different structures. The earthquake coefficient, C, may be determined from the relation:

$$C = \frac{ABI}{R_w} \qquad (2)$$

in which, A, B, I and R_w are the design base acceleration, the dynamic response coefficient, the importance factor and the performance factor, respectively. The design base acceleration, A, is given by seismic codes for different localities. This coefficient is, however, determined for the horizontal earthquake loading and should be modified for the vertical loading. For design of jack arch slabs, the importance factor, I, may be taken as that for the whole building. The other two coefficients need further considerations as follow:

Dynamic Response Coefficient: B

This coefficient is a function of the soil type, T_o, and the fundamental period of vibration of the system, T, and represents the dynamic magnification of the system's response. For jack arch slab, the fundamental mode of vibration will be the first out-of-plane bending mode. A simple method of determining T, for the jack arch slabs, is discussed in [2] and is given by the following relation

$$T = \frac{2\pi a^2}{\lambda_1^{\,2}\left[\dfrac{E_{eff}h^3}{12\rho(1-\vartheta_m^{\,2})}\right]^{1/2}} (\text{sec.}) \qquad (3)$$

In the above equation, a, h, E_{eff}, ρ, υ_m are length, thickness, effective elastic modulus, mass per unit area and Poisson's ratio of the plate, respectively and λ_1 is a dimensionless parameter depending on the geometry of plate and it's boundary conditions [5]. The effective elastic modulus, E_{eff}, of the slab has an appreciable effect on the fundamental period of vibration. A procedure for determining the E_{eff} is given in [2]. In figure (2) E_{eff} is given as a function of the weight of steel per unit area of slab, W_s (kg/m^2).

To determine the dynamic response coefficient, B, different seismic codes provide different relations and diagrams, the majority of which are based on T_o and T. These relations are derived for the building as a whole and, in most codes, the region in the diagram covering small periods of vibration is considered a constant maximum. The fundamental periods of vibration of jack-arch slabs are, however, well below those of ordinary buildings and sometimes fall within this range. It is, therefore, prudent to determine the actual values of B in this period range.

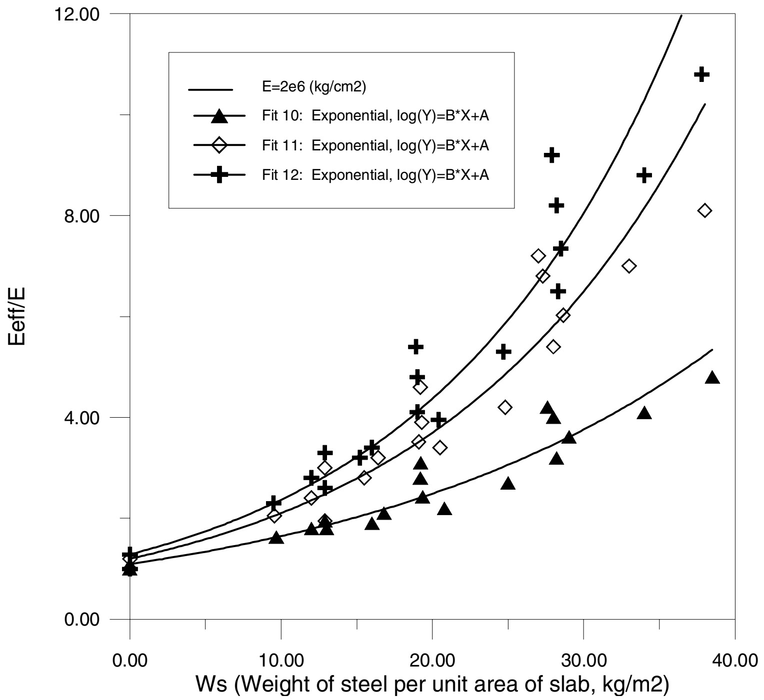

Fig. 2 Effective modulus of elasticity of the jack arch slab

Performance Factor of Jack Arch Slab, R_w

The jack arch slab system discussed here may be considered as a confined masonry construction. For confined masonry walls, a value of 4 is often used for the performance factor R_w [6]. However, the jack arch slab system is expected to behave differently to a conventional masonry building system. In general, the system performance factor, R_w, corresponding to the UBC allowable stress design format, is given by:

$$R_w = R_\mu \Omega Y \tag{4}$$

In which, R_μ, Ω and Y are; ductility reduction factor, overstrength factor and allowable stress factor, respectively. Design of jack arch slab will be based on designing the steel grid and controlling the brick arches for allowable stresses. Ductility of the slab, therefore, will depend on the level of stresses in the brick arches when the steel grid is at its allowable stress limit. The number and size of transverse beams in a two-way system will govern the ductility of the slab. Conservatively assuming no ductility for the one-way system (i.e. $R_\mu = 1$), a number of finite element stress analyses were conducted on slabs of different sizes and transverse beam configurations and, in each analysis, the level of stresses in brick arches were compared with those of the one-way system. This comparison was used as a basis for determining the available ductility of the slab. Results of these analyses are plotted in figure 3 in which, the ductility factor of the slab, R_μ, is plotted against the amount of transverse beams per unit area of the slab. A safe value of Ω =1.5 may be proposed for the overstrength of jack-arch slab. The allowable stress factor, Y, on the other hand may be determined by considering the critical element of the slab, i.e. the steel grid. For steel construction, Y, varies between 1.4 to 1.5. The performance factor, R_w, may therefore be considered as 2.0 ($R_\mu = 1.0$, $\Omega = 1.5$, $Y = 1.4$) for the one-way system and $2.1R_\mu$ for the two-way system.

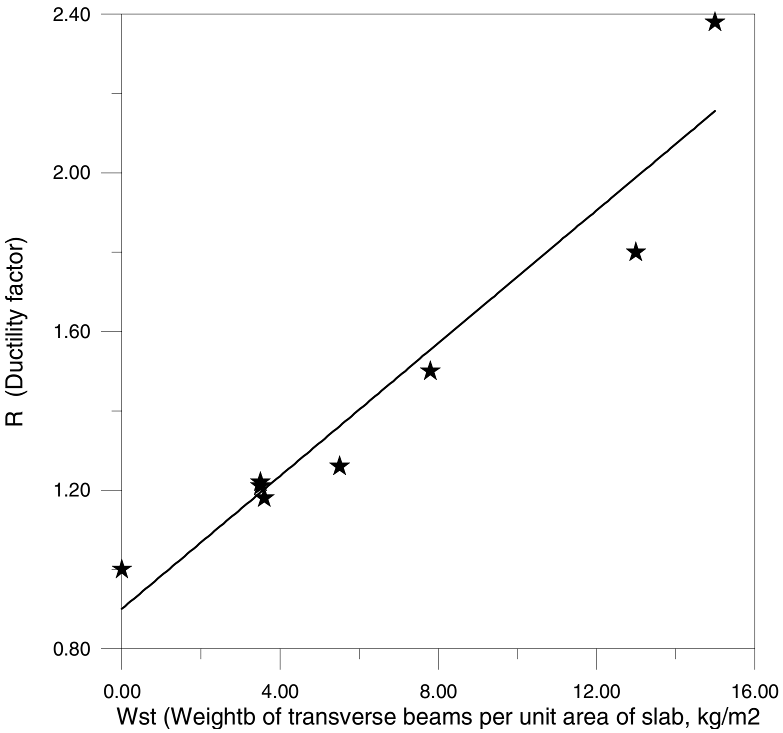

Fig. 3 Ductility factor R_μ as a function of the weight of transverse beams

DESIGN PARAMETERS

Similar to other slab systems, in the jack arch slab, there are a number of parameters that affect the design. The most important parameters in this respect are recognized as; (i) dimensions of the slab, (ii) layout of the steel grid, (iii) boundary conditions and connections of slab elements, (iv) width and rise of brick arches, (v) loading, W, (vi) elastic modulus of brickwork, E_m and (vii) allowable stress of brickwork (f_{mall}).

Allowable stresses

The allowable stresses for steel and masonry are determined by codes of practice. For this study, in line with the conventional codes of practice, allowable flexural tensile or compressive stress for steel will be assumed to be; $f_{sall} = 0.6 f_y$. Since no references exist concerning the allowable stresses used for jack arch masonry made with lime-clay mortar, the following are proposed [2].

Allowable compressive stress for masonry: $f_{mall} = 0.2 f'_m$

Allowable tensile stress for masonry: $f_{ball} = 100$ kPa

Dimensions and layout of slabs

Geometry and dimensions of the slab are governed by the architectural layout of the building. It is, however, a useful common practice to limit the span of the main beams to 6.0 m. For larger floor areas, deep or stiff support beams or girders will be necessary to reduce the effective span of the longitudinal dimension of the slab. In the proposed two-way system, if the transverse beams are to be effective in carrying some load, it will be necessary to limit the transverse dimension of the slab to twice the span of the main beam. This can be achieved by providing support beams

The number of main beams required for a jack arch slab will be determined by considering the transverse dimension of the slab and the width of brick arches. Within the limits discussed later, a designer may select an appropriate width of arch and determine the number of required main beams.

The span of main beams and the level of loading dictate the number of required transverse beams. One of the objectives of providing transverse beams is to divide the long brick arches into a number of smaller brick panels. The maximum distance between the transverse beams should preferably be fixed as twice the width of the arch. This would give brick panels of a maximum length to width ratio of 2.0. The number of required transverse beams and their section modulus, as design parameters, will depend on the level of horizontal and vertical loading.

Design of Reference Slabs (Design Table)

Over 350 individual rectangular slabs of different dimensions, ranging from 3.0x3.2m to 6.0x12.0m and different steel configurations were selected as reference slabs. Each slab was then designed with other design parameters ((iii) to (vi)) having reference values or conditions. These include; a non-yielding support for the main beams (α =1.0), a width of brick arch equal to 80cm with a rise of 5cm (β =1.0), an equivalent vertical load of W = 10.0 kN/m^2 (ω = 1.0), a brickwork elastic modulus of E_m =2.5 MPa (ε = 1.0) and an allowable compressive stress for brickwork of f_{mall} = 1.0 MPa (λ = 1.0). In the above, α, β, ω, ε and λ are penalty factors, values of which are unity for design parameters with reference values. For design parameters having values other than those specified above, these factors assume different values as will be discussed later.

For each slab, the required section modulus, S_n and moment of inertia, I_n of the main and transverse beams were thus determined using the allowable stress limits for steel and brick arches and deflection limits (discussed later) as controlling parameters. For an optimum design of the main steel beams and in line with design procedures for RC slabs, the jack arch slab is divided into three strips; a central strip and two side strips. Unlike the RC slab, this division cannot be made on a fixed length and, therefore, the division is made on the number of main beams. It should be noted that, if slab beams span over two or more slab panels, the negative moments in side beams become critical. In this case, all main beams should be of the same size as the central beams.

The results of the design of each reference slab in the form of the evaluated section modulus, S_n and moment of inertia, I_n of the steel beams are compiled in a table referred to as "design table". A typical section of the design table is shown in Table 1. The complete design table is presented elsewhere [3]. For every slab size, different steel grid configurations are presented in the table which, include both the one-way and two-way systems. All the given configurations will be suitable for a design coefficient of C_s =1.0, based on vertical gravity and seismic loads only. The required moments of inertia of the main and transverse beams, I_{req}, will be determined from the following equation;

$$I_{req} = C_s I_n \tag{5}$$

where,

$$C_s = \alpha\beta\omega\varepsilon\lambda \tag{6}$$

In Eqn. (5), I_n, is the minimum moments of inertia of the main and transverse beams, given in the design table and α, β, ω, ε and λ are the factors discussed later. The actual design for every steel configuration is carried out by designer using I_{req}. Design coefficient, C_s, will be applied to both the main and transverse beams.

In earthquake prone areas, the slab may undergo horizontal in-plane shear forces for which it should be controlled. In another set of analyses, the in-plane shear strengths of all steel grid configurations for every slab size were calculated and presented in the design table. In this way, the choice of a particular configuration for a given slab size will depend on two parameters, namely; the level of in-plane shear force on the slab and the economy of steel configuration. A designer will choose the cheapest steel configuration, which is capable of resisting the given in-plane shear force.

Table 1. Typical format of design table

Slab dimensions (m)	Minimum normalized moments of Inertia (I_n) and the section modulus (S_n)									In-plane shear capacity of slab (kN)
	Main beams						Transverse beams			
	Central beams			End beams						
	No.	S_n (cm^3)	I_n (cm^4)	No.	S_n (cm^3)	I_n (cm^4)	No.	S_n (cm^3)	I_n (cm^4)	
3.0x3.2	1	146	1320	2	78	541	-	-	-	
	1	109	869	2	53	318	1	53	318	30
	1	78	541	2	53	318	1	109	869	
	3	78	541	-	-	-	1	53	318	
	1	109	869	2	53	318	2	53	318	40
	3	78	541	-	-	-	2	53	318	
	1	78	541	2	53	318	2	109	869	
3.0x4.0	2	146	1320	2	78	541	-	-	-	-
	2	109	869	2	53	318	1	53	318	40
	4	78	541	-	-	-	1	53	318	
	2	78	541	2	53	318	1	146	1320	
	2	84	600	2	53	318	2	53	318	55
	4	78	541	-	-	-	2	53	318	
	2	78	541	2	53	318	2	78	541	

PARAMETRIC EVALUATION OF DESIGN PARAMETER FACTORS

To design a jack arch slab with design parameters having different values to their reference values, conversion factors are necessary to account for the effects of the change in the values on the design. For this purpose a series of parametric analyses were conducted on 15 different jack arch slabs, covering a wide range of slab sizes and steel grid configurations in which the effect of each design parameter on the outcome of the design was evaluated. The slab dimensions considered included; 3.0 by 3.2, 3.0 by 5.6, 4.5 by 4.8, 4.5 by 8.8, 6.0 by 6.4 and 6.0 by 12.0m and steel grid configurations included; (a) no transverse beams (one-way system), (b) one transverse beam and (c) two transverse beams. Other parameters were kept constant throughout the parametric study when not under study, with reference values.

Slab support condition (factor, α)

The jack arch slab may be supported on walls or deep beams, in which case, the deflection of the slab on the line of its support will be nil or negligible. The flexible beams of a framed building may also support the slab. In this case, the slab will deflect on the support lines with the supporting beams. This changes the stress level in the steel beams and the brick arches. All the analyses leading to the design table were made assuming the former, unyielding support condition for the main beams and the latter, flexible support condition for the transverse beams. A factor, α, was therefore calculated to account for other forms of support conditions. In Table 2 the correction factor, α, indicating the required change in the moment of inertia of steel sections, is given for slabs of different sizes and steel grid configurations.

Table 2. Support condition factor, α

Slab dimensions (m)	*Type of slab*	*Support conditions*			
		Main-flex. Trans.- rigid	*All baems flexible*	*All beams rigid*	*Main-rigid Trans.-flex.*
3.0x3.2	*One-way*	*0.80*	*1.0*	*0.80*	*1.0*
	Two-way (1)	*0.64*	*0.74*	*0.77*	*1.0*
	Two-way (2)	*0.60*	*0.75*	*0.77*	*1.0*
3.0x5.6	*One-way*	*0.83*	*0.95*	*0.84*	*1.0*
	Two-way (1)	*0.92*	*0.87*	*0.93*	*1.0*
	Two-way (2)	*0.82*	*0.95*	*0.94*	*1.0*
4.5x4.8	*One-way*	*0.92*	*0.97*	*0.92*	*1.0*
	Two-way (1)	*0.82*	*0.87*	*0.92*	*1.0*
	Two-way (2)	*0.80*	*0.92*	*0.93*	*1.0*
4.5x8.8	*One-way*	*0.95*	*0.97*	*0.93*	*1.0*
	Two-way (1)	*0.96*	*0.06*	*0.98*	*1.0*
	Two-way (2)	*0.95*	*0.03*	*0.95*	*1.0*
6.0x6.4	*One-way*	*0.91*	*0.98*	*0.96*	*1.0*
	Two-way (1)	*0.85*	*0.92*	*0.98*	*1.0*
	Two-way (2)	*0.88*	*0.95*	*0.97*	*1.0*
6.0x12.0	*One-way*	*0.91*	*0.97*	*0.96*	*1.0*
	Two-way (1)	*0.93*	*0.94*	*0.95*	*1.0*
	Two-way (2)	*1.02*	*1.02*	*1.03*	*1.0*

Width of Brick Arches (factor, β)

In the construction of traditional jack arch slabs, the width of arch varies from 80 cm to 1.0 m. Wider arches require a higher rise and, therefore, a thicker slab and shorter arches mean extra steel beams. The rise of arch is another important parameter affecting the performance of the slab. Numerical analyses carried out on slabs having different arch widths showed optimum width to rise ratio of 16. It is, therefore, recommended that, when geometry of the slab dictates using shorter arches, the rise of arch to be taken as 5 cm and when a wider arch (up to 100 cm) becomes necessary, the rise of arch should correspond to the width to rise ratio of 16.

The reference width of arch used for design table analyses is 80 cm. When a wider arch is used, a factor, β, should be applied to the supporting steel beams to take into account the increased stresses in the brick arches. This factor for different widths of arch is given in Table 3.

Table 3. Width of brick arch factor, β

Slab dimensions (m)	*Type of slab*	*Width of arch*		
		100 cm	*90 cm*	*80 cm*
3.0x3.2	*One-way*	*1.44*	*1.22*	*1.0*
	Two-way (1)	*1.10*	*1.0*	*1.0*
	Two-way (2)	*1.05*	*1.0*	*1.0*
3.0x5.6	*One-way*	*1.44*	*1.22*	*1.0*
	Two-way (1)	*1.25*	*1.12*	*1.0*
	Two-way (2)	*1.24*	*1.12*	*1.0*
4.5x4.8	*One-way*	*1.46*	*1.23*	*1.0*
	Two-way (1)	*1.31*	*1.14*	*1.0*
	Two-way (2)	*1.28*	*1.15*	*1.0*
4.5x8.8	*One-way*	*1.44*	*1.22*	*1.0*
	Two-way (1)	*1.32*	*1.16*	*1.0*
	Two-way (2)	*1.25*	*1.13*	*1.0*
6.0x6.4	*One-way*	*1.46*	*1.23*	*1.0*
	Two-way (1)	*1.30*	*1.15*	*1.0*
	Two-way (2)	*1.30*	*1.16*	*1.0*
6.0x 12.0	*One-way*	*1.44*	*1.21*	*1.0*
	Two-way (1)	*1.32*	*1.16*	*1.0*
	Two-way (2)	*1.39*	*1.22*	*1.0*

Loading, W (factor, ω)

Loading is a design parameter calculated by the designer. The design table is based on an equivalent static, vertical load of 10.0 kN/m^2. A factor is, therefore, necessary to account for variations in the load intensity. The value of this correction factor for loading other than reference loading is listed in Table 4.

Elastic Modulus of Brickwork, E_m (factor, ε)

Similar stress analyses to those mentioned above were carried out on the selected slabs, this time changing the variable parameter to elastic modulus of brickwork. Values between 2.5 GPa and 20.0 GPa were used for E_m in different analyses. The value of elastic modulus used as a basis for comparison was taken as $E_m = 2.5$ GPa which, corresponds to the elastic modulus of the lightweight, perforated brick-lime mortar prism. The steel sections required to bring the maximum stress in brick arches to the level of the reference slabs ($E_m = 2.5$ GPa) were then normalized to the steel sections of the reference slabs. The normalized values are equivalent to a factor, ε, which is found to be proportional to E_m in the following form;

$$\varepsilon = 1.0 + 0.4(E_m - 2.5) \qquad (E_m \text{ in GPa}) \qquad (7)$$

Allowable Stress of Brickwork, f_{mall} (factor, λ)

The allowable compressive stress of brickwork used to evaluate the design table was assumed as 1.0 MPa ($f_{mall} = 0.2 f'_m$). For allowable stresses, $f_{mall} \neq 1.0$ MPa, another factor, λ, is used. The values of this correction factor are given in Table 5. Table 5 has similarly been extracted from analyses in which steel sections for different values of f_{mall} were calculated.

Table 4. Design load factor, ω

Slab dimensions (m)	*Type of slab*	*Load (ton/m^2)*				
		1.5	*1.2*	*1.0*	*0.8*	*0.5*
3.0x3.2	*One-way*	*1.85*	*1.35*	*1.0*	*0.75*	*0.34*
	Two-way (1)	*1.70*	*1.20*	*1.0*	*0.65*	*0.41*
	Two-way (2)	*1.70*	*1.25*	*1.0*	*0.70*	*0.37*
3.0x5.6	*One-way*	*1.75*	*1.34*	*1.0*	*0.75*	*0.38*
	Two-way (1)	*1.70*	*1.30*	*1.0*	*0.74*	*0.40*
	Two-way (2)	*1.72*	*1.31*	*1.0*	*0.75*	*0.39*
4.5x4.8	*One-way*	*1.69*	*1.33*	*1.0*	*0.78*	*0.43*
	Two-way (1)	*1.62*	*1.22*	*1.0*	*0.74*	*0.44*
	Two-way (2)	*1.65*	*1.25*	*1.0*	*0.76*	*0.44*
4.5x8.8	*One-way*	*1.67*	*1.34*	*1.0*	*0.78*	*0.44*
	Two-way (1)	*1.62*	*1.30*	*1.0*	*0.75*	*0.42*
	Two-way (2)	*1.60*	*1.26*	*1.0*	*0.75*	*0.43*
6.0x6.4	*One-way*	*1.64*	*1.33*	*1.0*	*0.78*	*0.45*
	Two-way (1)	*1.62*	*1.24*	*1.0*	*0.72*	*0.45*
	Two-way (2)	*1.63*	*1.27*	*1.0*	*0.76*	*0.45*
6.0x12.0	*One-way*	*1.62*	*1.30*	*1.0*	*0.78*	*0.45*
	Two-way (1)	*1.60*	*1.24*	*1.0*	*0.75*	*0.44*
	Two-way (2)	*1.64*	*1.25*	*1.0*	*0.77*	*0.47*

Table 5. Factor for allowable stress of brickwork, λ

Slab dimensions (m)	*Type of slab*	*Brickwork allowable stress f_{mall} (kg/cm^2)*					
		30.0	*25.0*	*20.0*	*15.0*	*10.0*	*8.0*
3.0x3.2	*One-way*	*0.13*	*0.20*	*0.33*	*0.55*	*1.0*	*1.40*
	Two-way (1)	*0.22*	*0.33*	*0.40*	*0.52*	*1.0*	*1.25*
	Two-way (2)	*0.16*	*0.27*	*0.38*	*0.52*	*1.0*	*1.32*
3.0x5.6	*One-way*	*0.13*	*0.21*	*0.32*	*0.52*	*1.0*	*1.33*
	Two-way (1)	*0.24*	*0.30*	*0.38*	*0.55*	*1.0*	*1.28*
	Two-way (2)	*0.20*	*0.28*	*0.32*	*0.54*	*1.0*	*1.30*
4.5x4.8	*One-way*	*0.24*	*0.31*	*0.38*	*0.62*	*1.0*	*1.32*
	Two-way (1)	*0.23*	*0.30*	*0.39*	*0.58*	*1.0*	*1.33*
	Two-way (2)	*0.26*	*0.32*	*0.42*	*0.59*	*1.0*	*1.32*
4.5x8.8	*One-way*	*0.24*	*0.32*	*0.44*	*0.62*	*1.0*	*1.35*
	Two-way (1)	*0.25*	*0.32*	*0.43*	*0.61*	*1.0*	*1.25*
	Two-way (2)	*0.27*	*0.32*	*0.43*	*0.62*	*1.0*	*1.27*
6.0x6.4	*One-way*	*0.27*	*0.34*	*0.44*	*0.64*	*1.0*	*1.32*
	Two-way (1)	*0.27*	*0.35*	*0.44*	*0.62*	*1.0*	*1.32*
	Two-way (2)	*0.27*	*0.34*	*0.44*	*0.62*	*1.0*	*1.28*
6.0x12.0	*One-way*	*0.28*	*0.35*	*0.45*	*0.63*	*1.0*	*1.37*
	Two-way (1)	*0.27*	*0.35*	*0.43*	*0.61*	*1.0*	*1.25*
	Two-way (2)	*0.27*	*0.37*	*0.35*	*0.63*	*1.0*	*1.35*

Control of deflection

Control of deflection is an important aspect of structural design. This is particularly true for the jack arch slabs as they are generally more flexible than the conventional concrete slabs. Some codes of practice suggest a maximum allowable out-of-plane deflection of, $\Delta_{max} = l/360$. This limit has been used for control of deflections in jack arch slab design. For every slab size and steel configuration presented in the design table, the maximum out-of-plane deflection of the slab was determined from the numerical analyses. This deflection was in turn compared with the maximum allowable deflection and the necessary changes in the design parameters, required to reduce the deflection to the allowable limit and keep the stresses in brick arches and steel beams within their specified allowable stresses, were calculated. A deflection parameter, γ, was then calculated as;

$$\gamma = \alpha\beta\varepsilon\lambda \geq \gamma_{min} \qquad (8)$$

This process was repeated for all the slabs considered. The maximum values of deflection control parameter evaluated for different slab types were, therefore, selected as the controlling limits (γ_{min}).

DESIGN PROCEDURE

Based on the loading and design parameters discussed above, the following procedure is proposed for design of one-way and two-way jack arch slabs:

Initial Design of Slab

i) Considering the dimensions of the slab, select the number of required main beams. Adjust the width of arch to match the actual dimensions of the slab (use wider arches at the ends and smaller arches at the center).

ii) From the design table select the number of transverse beams required to control the in-plane shear force on the slab (calculated from the seismic loading of the building).

iii) From the selected steel configuration in design table determine the moments of inertia of the main and transverse beams, I_n.

iv) Calculate an initial load parameter, ω, from Table 4, assuming W as the sum of service dead load and live load only (This step will be useful for a more representing initial design).

v) Calculate initial I_{req} for beams from Eqn. 5, assuming $C_s = \omega$.

vi) Select steel sections using I_{req} .

Design Loads

vii) Calculate the vertical earthquake load using Eqn. (1) to Eqn. (4).

viii) Determine the critical service gravity and vertical earthquake load combination, W (design load), using any appropriate code recommendations (i.e. D + L or φ(D + L + E), etc.).

Correction Factors

ix) Considering the slab support condition, determine the slab support correction factor, α, using Table 2.

x) If width of arch > 80 cm, determine the width of arch correction factor, β, using Table 3.

xi) Determine the vertical load correction factor, ω, using the calculated design load, W, and Table 4.

xii) If $E_m \neq 2.5$ GPa, determine the E_m correction factor, ε, from Eqn. (7)

xiii) If $f_{mall} \neq 1.0$ MPa, determine f_{mall} correction factor, λ, from Table 5.

xiv) Calculate deflection control parameter, γ, from Eqn. (8). Check that $\gamma > \gamma_{\min}$, if not ;
$\gamma = \gamma_{\min}$

xv) Calculate design coefficient C_s, $(C_s = \gamma\omega)$.

Final Design of Slab

xvi) Determine the I_{req} for the beams of the selected configuration using C_s and Eqn. (5). If necessary, change the size of the main and transverse steel sections to suit the required moments of inertia, I_{req}.

Note: The change in the size of steel sections may alter the vertical design load. This change would not affect the other parameters. A recalculation of design load will be necessary as stated in step (xvii).

xvii) If in step (xvi) steel sections are changed, repeat steps; (vii), (viii), (xi), (xv) and (xvi).

xviii) Control the in-plane shear force against the shear capacity of the designed slab (design table). If necessary, increase the size of transverse beams.

CONCLUSIONS

The performance of the anchored jack arch slabs in Bam, Iran earthquake of December 2003, supports previously reported findings of experimental and numerical investigations that the engineered form of the jack arch slabs can resist dynamic loading of high magnitudes and therefore are well suited as flooring systems in earthquake prone areas. The ability of the slab to act as a diaphragm and the apparent high ductility of the slab as observed in recent earthquakes and noted in numerical and experimental studies are two major factors supporting the above notion.

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